DESIGN AND PERFORMANCE OF WIRELESS SENSORS FOR STRUCTURAL HEALTH MONITORING

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ABSTRACT. Wireless sensors can be realized by integrating a sensor with a passive commercial radio-frequency identification (RFID) chip. When activated, the chip responds with a digitally encoded signal that not only identifies the sensor but also contains information about the sensor state. Two devices have been developed to date: a temperature-threshold indicator and a chloride-threshold indicator. This paper discusses basic concepts, design issues, and preliminary performance.

INTRODUCTION

SRI International is currently developing a series of wireless sensors for various applications in structural health monitoring. These devices are based on integrating a sensor with a commercial radio-frequency identification (RFID) chip (also called a tag because of its widespread use in inventory control). The chip is passive and is activated by inductively coupled power from a remote interrogator/reader. When activated, the chip responds with a digitally encoded signal that not only identifies the sensor, but also contains information about the sensor state. To date, we have developed two devices. One indicates whether a particular temperature threshold has been exceeded and is intended for monitoring the heat exposure of the material underneath the thermal protection system (tiles) on the Space Shuttle [1]. The other device is being designed to monitor the level of chloride ingress into concrete bridge decks, with an ultimate goal of including these sensors in the concrete pour when the deck is constructed. This paper discusses the basic concepts and design issues associated with such RFID/sensor hybrids and presents information on preliminary performance.

BASIC CONCEPTS

The principle of operation of an RFID/sensor hybrid is illustrated in Fig. 1. The operation of this system can be described as follows. First, the radio-frequency (RF) transceiver (called an interrogator or reader) illuminates the embedded microsensor. The power incident on the microsensor is rectified to produce the DC power needed to operate the microsensor. Next, the backscatter from the microsensor antenna (coil) is modulated by the RFID chip according to the ID code and sensor state in the RFID memory. Finally, the

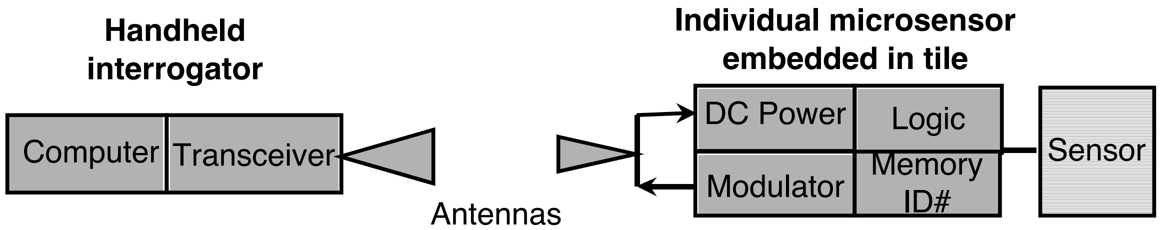

FIGURE 1. Principle of operation of an RFID/sensor hybrid.

transceiver demodulates the received backscatter and reports the ID and sensor state to the computer. If desired, the computer can then update a database for the structure being monitored and flag particular locations for further inspection and/or maintenance.

RFID chips can be purchased from a number of different manufacturers, but we have used those made by Microchip Technology, Inc.[1], namely, the MCRF200 and MCRF202. These chips both use an interrogating frequency of 125 kHz but differ in that the MCRF202 contains a sensor port that can be used to invert the bit stream associated with the ID code and a V_{cc} port for powering external electronics (up to 10 microwatts). We have coined the term SensorTag™ to represent our particular realization of an RFID/sensor hybrid for the Space Shuttle thermal-protection-system application[2] (to be discussed later). An electrical equivalent circuit for the system schematized in Fig. 1 is shown in Fig. 2.

The inductive coupling between the reader and SensorTag™ is represented in this circuit by the mutual inductance M_{21}. The inductance in the reader circuit is series resonated to maximize the current through the reader antenna. This technique maximizes the magnetic field generated at the SensorTag™ antenna. In contrast, the inductance in the SensorTag™ circuit is parallel resonated to maximize the voltage across the antenna. This technique maximizes the peak RF voltage that is rectified to power the RFID chip.

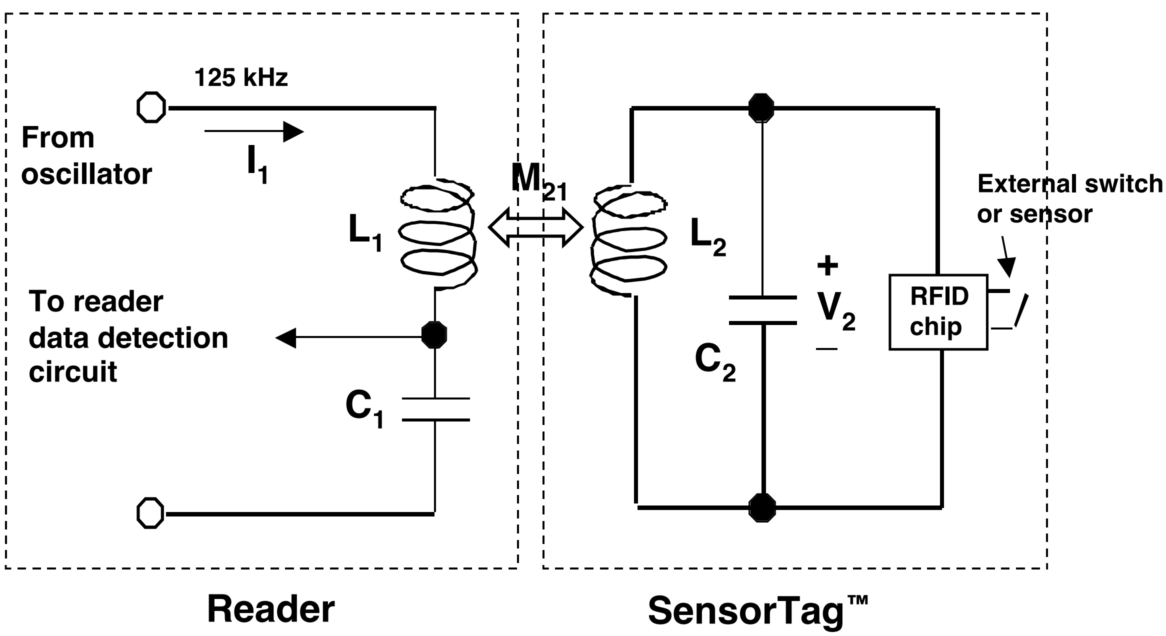

FIGURE 2. Equivalent circuit.

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[1] Microchip Technology, Inc., 2355 West Chandler Blvd., Chandler, AZ 85224-6199

[2] Wireless Event-Recording Devices With Identification Codes, patent pending.

The design of the antenna coils is driven largely by the desire to maximize the mutual inductance between them. To illustrate the coil design parameters that come into play, consider the equation for the mutual inductance between two coaxial coils, viz.,

$$M_{21} = \frac{\mu_{eff}\mu_0 \pi R_1^2 R_2^2 N_1 N_2}{2\left(D^2 + R_1^2\right)^{3/2}}. \tag{1}$$

Although this mutual inductance depends on the effective permeability, $\mu_{eff}\mu_0$, of the tag coil core and the distance between coils, D, the most important intrinsic tag coil parameters are its radius, R_1, and its number of turns, N_1. Thus, we want to make the tag coil diameter and number of turns as large as possible without exceeding space limitations or causing the coil to be self-resonant at the operating frequency. A further constraint is that the self inductance of the tag coil should not be so large that the resonating capacitor is too small to be practical (i.e., it should be at least 10 pF).

A photograph of the coil constructed for the SensorTag™ is shown in Fig. 3. This coil consists of about 1000 turns of AWG 52 copper wire wound in 4 layers on a 0.030-in.-diameter ferrite core. The outer diameter of the coil is about 0.040 in. The ferrite core is Fair-Rite 61 material[3] which has a Curie temperature of 350° C (662° F) and which provides an effective permeability of 45 with these coil dimensions. A wire with polyimide insulation was used to withstand high temperatures (300° C). The fine wire used here (about 0.001-in. in diameter) had a resistance of 17 ohms/ft, which results in a total coil resistance of 142 ohms and an unloaded coil Q of about 20 at 125 kHz. The loaded Q will be less than the unloaded Q, so the antenna bandwidth is more than adequate for handling the modulation rates (a few kHz) used by the chips mentioned above.

We have devised two different concepts for determining the sensor state from the detected ID data, depending on which Microchip RFID device is used. For the MCRF200 we used a frequency-shift concept and for the MCRF202 we will be using a bit-stream inversion concept. The circuits for implementing these two concepts are shown diagrammatically in Figs. 4 (a) and (b), respectively. In the first concept two resonating capacitors are used to establish resonant frequencies sufficiently far apart from each other.

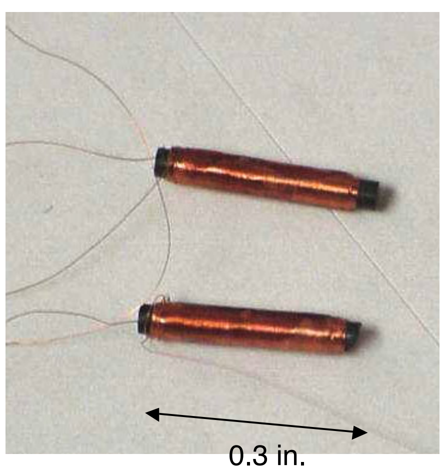

FIGURE 3. Photograph of SensorTag™ coils.

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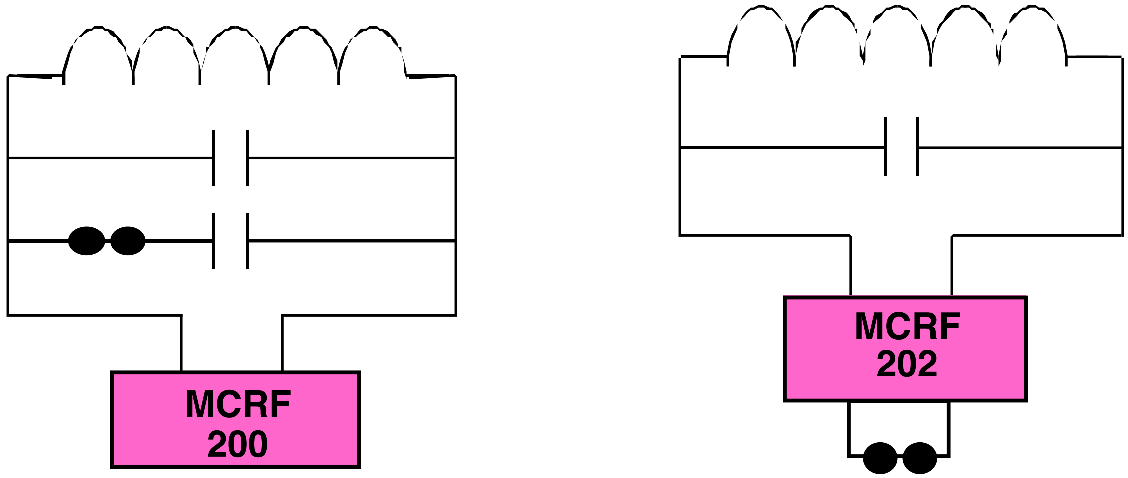
[3] Fair-Rite Products Corp., One Commercial Row, Wallkill, NY 12589-0288



(a) Frequency shift (b) Bit-stream inversion

FIGURE 4. Sensor-state indication concepts (From [1], reprinted with permission).

Thus, when the fuse (depicted by the two black dots) is closed, the RFID chip achieves its maximum response at one frequency and, when the fuse is open, its maximum response is at a different frequency. Although this approach can be made to work, its disadvantages are that (1) a two-frequency reader is required and (2) an ambiguous reading can be obtained if the reader is held too close to the SensorTag™. The second concept does not have these disadvantages since the sensor state is indicated unequivocally by an inversion of the ID code when the fuse opens. Of course, the reader must be able to tell the difference between the two codes. The bit-stream-inversion concept will also work if the fuse (switch) is replaced by a suitable voltage-level change, such as the output from a comparator.

Finally, the concept of "tag collision" should be mentioned. In practice, more than one SensorTag™ may be in the reader's interrogating field at one time. The overlapping signals that this situation produces can lead to reader confusion and prevent a reading from taking place. Hence the name *tag collision*. It is important, therefore, to implement a method for distinguishing between different, but adjacent, SensorTags™. Such a method is called an *anti-collision* algorithm. Different RFID tag manufacturers have implemented different anti-collision algorithms, but the details are often proprietary. One approach would be to have each tag transmit in a random time slot and have the reader search in different time slots and reject multiple readings of the same tag. Obviously, having an anti-collision capability is extremely important for most applications. The Microchip MCRF202 can be programmed to support anti-collision communications.

APPLICATION TO SPACE SHUTTLE THERMAL PROTECTION SYSTEMS

The Space Shuttle surfaces typically experience very high temperatures during reentry (1000s of degrees F). Hence, thermal protection systems (TPS) have been devised to prevent the vehicle from burning up. One prominent TPS system is composed of 4-in.-thick light-weight ceramic tiles that are attached to the underlying metal skin by high-temperature RTV adhesive. Generally, the tiles are separated from one another by small gaps, as is sketched in Fig. 5. Hot gases sometimes penetrate these gaps and char the underlying RTV. Hence all of these tiles must be inspected after each flight, and any tiles that are in danger of coming off must be replaced. This procedure is labor-intensive and

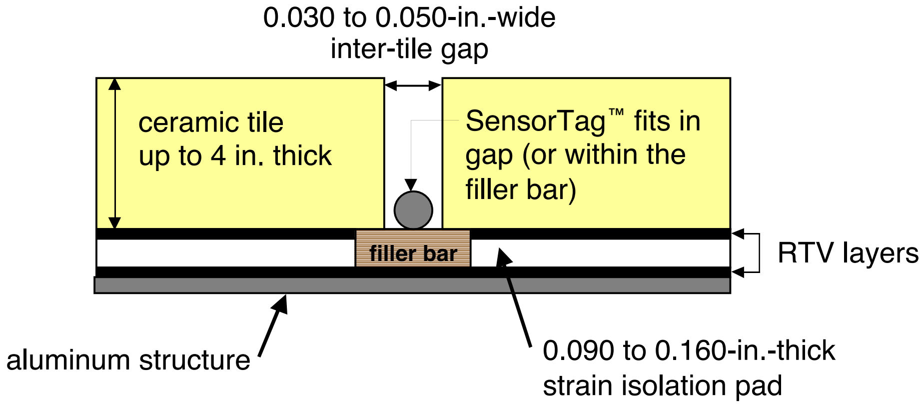


FIGURE 5. Cross-section sketch of typical TPS tile stack (not to scale) (From [1], reprinted with permission).

time-consuming. Thus there is a need to speed up this inspection/repair process and greatly reduce the turnaround time required to prepare the Shuttle for its next flight.

The SensorTag™ we have devised is designed to further this goal. It must fit in the gap between the tiles (Fig. 5) and its purpose is to indicate whether the temperature near the RTV has exceeded the RTV's charring threshold (550° F). This is accomplished by using a fuse in the SensorTag™ that opens at this temperature. Each SensorTag™ can be interrogated rapidly and, when an over-temperature indication is recorded, that tile is flagged for further inspection and replacement[4]. At the same time, this information can be entered automatically in a database that chronicles tile maintenance. Of course, the tripped SensorTag™ must be replaced at the same time as the damaged tile.

The fuse is a critical component in the SensorTag™. It must melt at just the right temperature. We achieved this requirement by using an appropriate eutectic solder. We found that a mixture of 90% Pb, 5% Ag, and 5% Sn melts at 558° F, which is quite close to our desired threshold temperature[5]. The layout of our fuse design is shown in Fig. 6. This fuse is quite small in size, the length of the solder bridge being 0.016 in. Micromachined silicon fuse covers were made to enclose the melted solder and a small amount of flux. A photograph of an assembled high-temperature SensorTag™ is shown in Fig. 7.

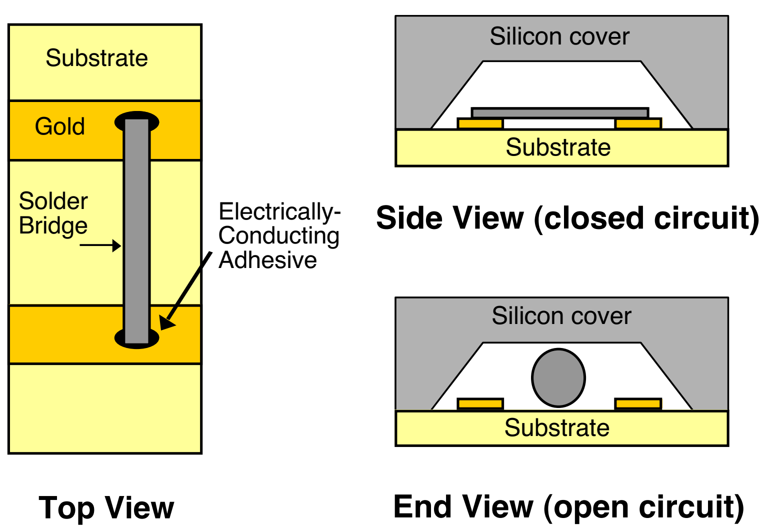


FIGURE 6. Thin-film microfuse layout (From [1], reprinted with permission).

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[4] The location of each tile is determined by its ID code, which has been recorded previously on a "map" of each tile's position on the Shuttle's surface.

[5] Indium Corporation of America #155 solder.

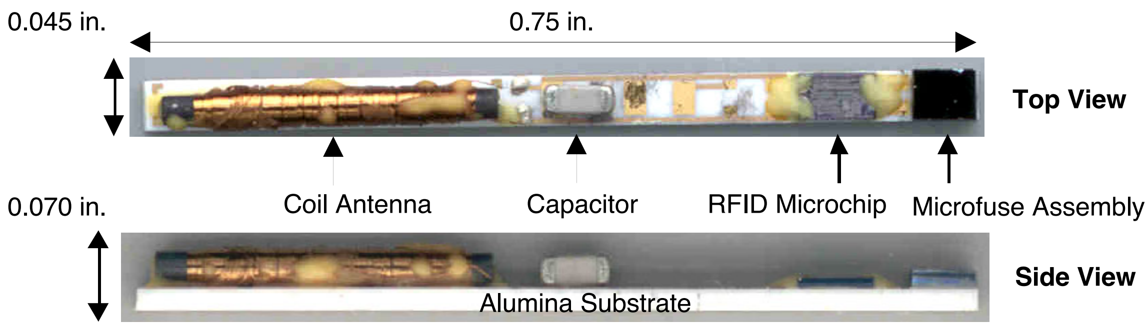

FIGURE 7. Photograph of prototype high-temperature SensorTag™ (From [1], reprinted with permission).

High-temperature arc-jet tests of an earlier, lower-temperature, prototype SensorTag™ were conducted at Ames Research Center in Mountain View, CA. A TPS tile was sectioned to simulate gaps between tiles and the gaps were instrumented with thermocouples and SensorTags™. A plasma jet of hot gases was passed over the surface of the tile and thermocouple temperatures were recorded. In some cases the temperature at the SensorTag™ exceeded its burnout temperature and caused failure, but where this did not happen the surviving SensorTags™ all gave correct indications when queried using a handheld reader to determine if their fuses had opened.

APPLICATION TO MONITORING CHLORIDE INGRESS IN BRIDGE DECKS

Another application where wireless threshold monitoring would be useful is in monitoring chloride ingress into concrete bridge decks. The problem here is that these structures contain steel rebar that will corrode in the presence of chloride ions. These ions diffuse into the concrete from the surface because of the presence of salt water from various sources such as seawater spray in coastal zones or deicing salts in cold climates. The diffusion rate is slow, but finite. The resulting corrosion leads to expansion of the rebar volume and subsequent cracking of the concrete. There is a critical chloride concentration level where such corrosion initiates and the goal would be to determine quickly and reliably when this level has been reached. Presently, concrete core samples have to be taken and analyzed in the laboratory. Moreover, it typically takes several years for the critical chloride concentration to be reached, so a number of tests may be required. Hence, it would be highly desirable to be able to test often and inexpensively.

Based on our work with SensorTags™, SRI International has devised a Smart Pebble™ concept wherein an RFID/sensor hybrid is encapsulated in a pebble-sized enclosure and embedded in the concrete bridge deck. This concept is illustrated in Fig. 8. For now, the Smart Pebbles™ are envisioned as being inserted in a back-filled non-concrete core for evaluation, but ultimately they would become part of the initial concrete pour. As of this writing, we are in the early stages of development and prototype devices have not yet been fabricated and tested.

A prime sensor candidate for this application is an electrochemical sensor that generates an electric potential dependent on the concentration of chloride ions. A possible circuit for such a Smart Pebble™ is shown schematically in Fig. 9. This circuit uses the MCRF202, which not only indicates when a threshold level has been exceeded by inverting the ID code bit stream, but which also is able to power the external electronics. The threshold level is set by the comparator design at the time of manufacture.

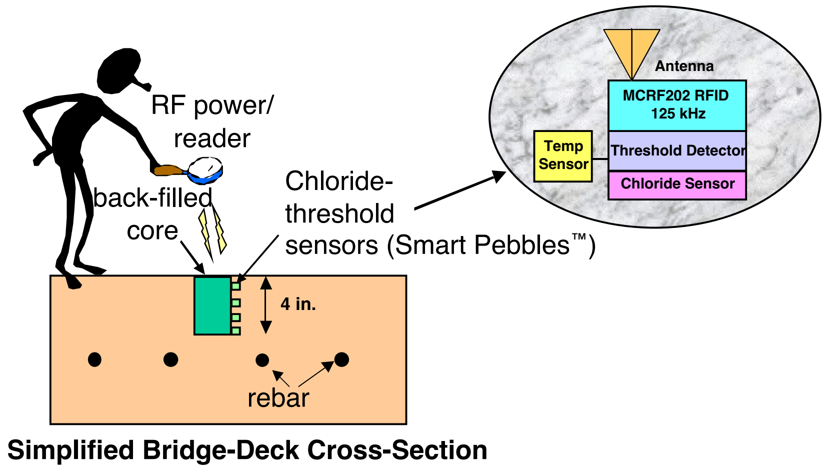

FIGURE 8. Smart Pebbles™ concept.

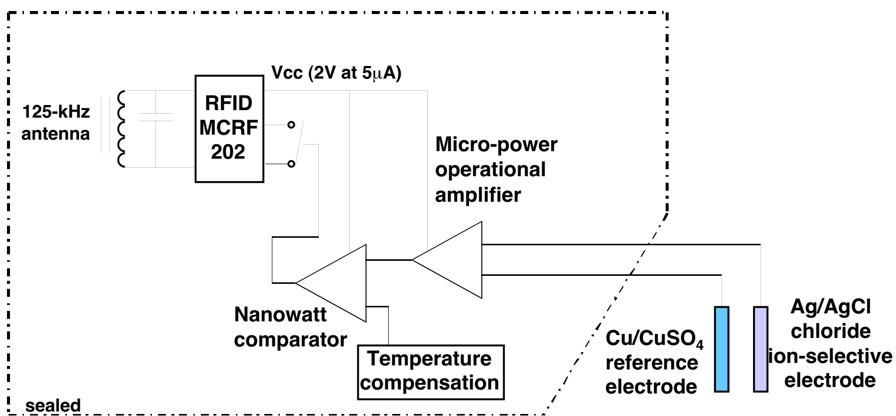

FIGURE 9. Potentiometric threshold measurement circuit with wireless communications.

The electrochemical sensor consists of two electrodes: an ion-selective electrode specifically for chloride ions and a reference electrode. The measured quantity in this case is the potential difference between these two electrodes. Thus, the potential of the reference electrode must remain fairly constant (say, ±5 mV) over the life of the Smart Pebble™. This requirement represents a major design challenge. The chloride sensor concept that we are currently evaluating is illustrated in Fig. 10.

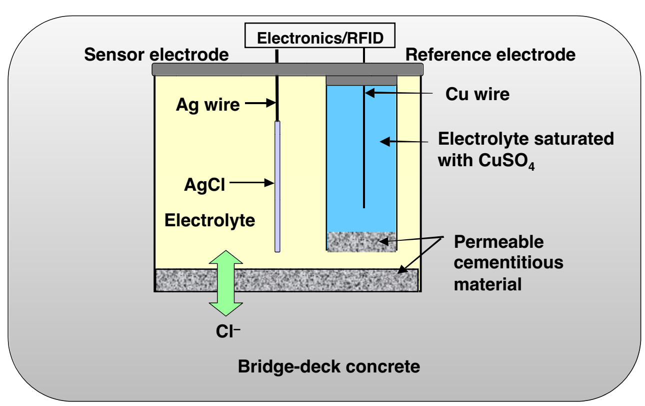

FIGURE 10. Chloride sensor concept.

SUMMARY

We have shown how commercial RFID devices can be used as the basis for implementing wireless sensors. Two such sensors have been described: a temperature-threshold sensor (SensorTag™) and a chloride-ion threshold sensor (Smart Pebble™). The SensorTag™ has been designed for monitoring the temperature at the base of the gaps between the thermal protection tiles on the Space Shuttle. The Smart Pebble™ is being developed for monitoring the ingress of chloride ions into concrete bridge decks.

SensorTags™ have been tested at high temperature in an arc jet and were found to perform as expected. Further developments that are required include reducing their size and increasing the read range. Note that these requirements are somewhat conflicting because the size of the SensorTag™ coil (antenna) has a strong effect on the read range (smaller antennas have shorter read ranges). One approach to overcoming this obstacle is to increase the operating frequency.

Smart Pebbles™ are in the early stages of their development. Laboratory tests using bit-stream inversion to indicate sensor state have been positive. Work is ongoing to develop a stable electrochemical sensor. Future work will include adding temperature-compensation circuitry and integrating all the components into a rugged 1-in.-diameter package. The goal of the present work is to eventually demonstrate the effectiveness of Smart Pebbles™ in real bridge decks.

ACKNOWLEDGEMENTS

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REFERENCE

1. Milos, F. S., Watters, D. G., Pallix, J. B., Bahr, A. J., and Huestis, D. L., “Wireless Subsurface Microsensors for Health Monitoring of Thermal Protection Systems on Hypersonic Vehicles,” in *Advanced Nondestructive Evaluation for Structural and Biological Health Monitoring,* Tribikram Kundu, Editor, Proceedings of SPIE Volume 4335, pp. 74-82 (2001).